Late quaternary activity of the Laguna Salada fault in northern Baja California, Mexico

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ABSTRACT

Faulted alluvial fans and bajadas along the central Laguna Salada fault zone in northern Baja California record a recurrent history of oblique-slip Holocene earthquakes. Alluvial surfaces, which range from late Pleistocene to historic in age have been progressively displaced along the base of the crystalline rangefront, as well as along more basinward fault splays in alluvium. The recurrence interval determined from displaced alluvial deposits that are dated by soil profile development is in the range of 1–2 ka, with a corresponding right lateral slip rate of ~2–3 mm/yr, similar to that of the southern Elsinore fault in southern California. The most recent event along the fault zone is probably the widely felt earthquake of February 23, 1892. At least 22 km of the fault zone ruptured during this event, along both an oblique-dextral section of the northwest-striking Laguna Salada fault and the linked, northeast-striking Cañon Rojo normal fault. The length of ground rupture and amount of displacement (4 m of dextral slip and 3.5 m of normal slip) suggest that the earthquake had a magnitude (Mw) of at least 7.1.

INTRODUCTION

Determination of the recent slip history of active fault zones commonly requires detailed subsurface data, which include boreholes, trenches, and earthquake locations. Studies of fault zones located in regions where these data are unavailable thus need to employ techniques based on readily available information. By studying fault scarp morphology and its relation to alluvial sedimentation, weathering, and soil development, it is possible to define the late Quaternary slip history of active faults where detailed subsurface information is unavailable. This requires recognition and mapping of offset geomorphic features and faults, along with the description, analysis, and comparison of soil profiles developed on alluvial surfaces. A critical aspect of this method is the recognition of small-scale topographic features offset across fault scarps to establish the recency and sense of slip on recent surface ruptures.

The Laguna Salada fault zone bounds the western margin of the Sierra Cucapa, an isolated northwest-trending mountain range in the southern Salton Trough (Fig. 1). This range and the adjoining Sierra Mayor extend 85 km from north of the international border to the southeast into Baja California and separate the southern Salton Trough into two regions of deep sedimentary fill, the Mexicali Valley and Laguna Salada basin (Fig. 1). The great variation in structural relief in basement rocks across these two basins and the intervening Sierra Cucapa is partly due to interaction among several northwest-striking dextral and oblique-slip faults. These include the Imperial, Cerro Prieto, Cucapa, Pescadores, Borrego, Laguna Salada, and Chupamiertos faults (Barnard, 1968), which partition dextral strain across the southern Salton Trough. These faults are part of the southern San Andreas fault system and mark the transition to transform faulting in the northern Gulf of California.

Major changes in structural relief, or uplifts and depressions, are present along the lengths of these faults (Fuis et al., 1982, 1984) and may coincide with stepovers or variations in fault strike. Releasing stepovers present in the Imperial and Mexicali Valleys include the Brawley and Cerro Prieto spreading centers (Fig. 1), (Muffler and White, 1969; Elders et al., 1972; Halfman et al., 1984) which link the San Andreas, Imperial, and Cerro Prieto dextral faults. Restraining stepovers along active dextral fault zones also exist in the Salton Trough and include the Durmid, Mecca, and Indio Hills along the San Andreas fault east of the Salton Sea (Bilham and Williams, 1985); the Ocotillo Badlands, Borrego Mountain, Superstition Mountain, and the Superstition Hills along the San Jacinto fault zone south of the Santa Rosa Mountains (Clark, 1972; Sharp and Clark, 1972; Sibson, 1986); and the Coyote Mountains and related structures along the Elsinore–Laguna Salada trend (Isaacs, 1987; Rockwell and Pinault, 1986; Rockwell, 1989).

Well-exposed releasing bends are also present along the eastern margin of the Laguna Salada basin (Mueller and Rockwell, 1991). The location of these fault stepovers defines the eastern limit of deep sediment fill in Laguna Salada and has governed the development of this basin during late Tertiary and Quaternary time (Biehler et al., 1964; Kelm, 1971; Mueller, 1984; Mueller and Rockwell, 1991). The northern Laguna Salada fault may be linked to the Elsinore fault in southern California across a complex zone of northeast- and northwest-striking faults in the Yuha basin area (Isaacs, 1987). Vertical separation is considerable in Laguna Salada, where up to 4–6 km of basin fill is present (Biehler et al., 1964; Kelm, 1971). Furthermore, fault rocks are exposed along parts of the Laguna Salada fault zone that appear to have been developed under conditions of cataclastic flow (Kerrich and Allison, 1978), suggesting significant vertical separation and uplift of the Sierra Cucapa.

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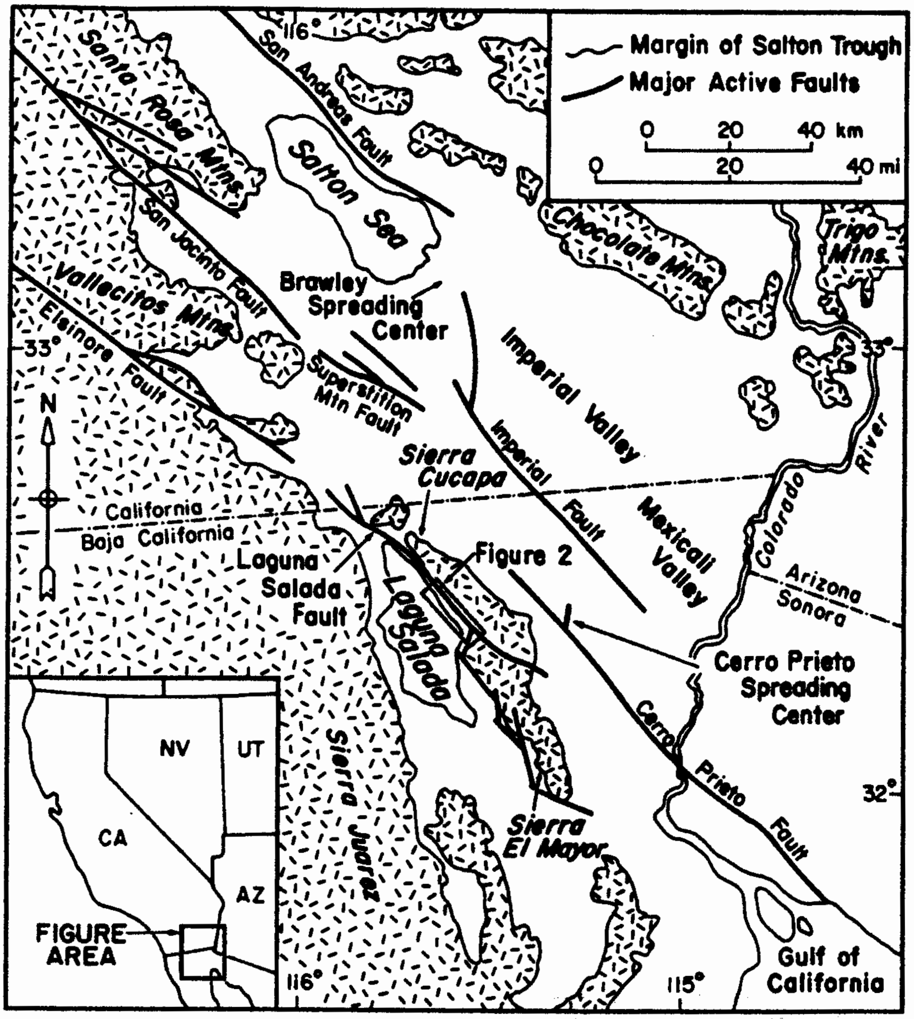


Figure 1. Simplified map of the Salton Trough, which outlines basement outcrops, Quaternary deposits, major faults, and the area mapped on Figure 2, located along the southwestern margin of the Sierra Cucapa, Mexico.

The total amount of slip along the Laguna Salada fault is presently unknown, although we believe it to be <20 km based on the amount of slip documented on the linked Elsinore fault in southern California. Total dextral slip across the northern Elsinore fault does not exceed 15 km (Hull, 1990; Morton and Miller, 1987), whereas parts of the southern Elsinore fault may transfer ~2–3 km (Lampe et al., 1988).

The fault is well expressed at the surface as a zone of well-preserved fault scarps and displaced alluvial fans (Mueller, 1984). In particular, well-preserved alluvial free faces and bedrock fault surfaces are exposed along much of the fault and may be the result of an historic earthquake and associated surface rupture. We mapped the active fault traces and studied the morphology of the scarps to resolve the sense and recency of slip along the Laguna Salada fault zone. The slip rate and recurrence interval of the fault was determined by description of soils developed in the displaced deposits and by comparison to dated soils developed under similar climatic conditions in southern California.

METHODS

The southwest margin of the Sierra Cucapa was mapped at a scale of 1:10 000, including the central Laguna Salada fault zone and the northeastern, most recently active segment of the Cañon Rojo fault (Figs. 1 and 2). Features mapped in the area include fault traces and scarps, deflected stream channels, displaced alluvial fans, and other alluvial surfaces. Individual alluvial surfaces and the underlying deposits were delineated by the degree of maturity of the soils developed in them and by other surface weathering characteristics such as clast disintegration and the development of rock varnish and desert pavement.

The magnitude and sense of displacement for the most recent earthquake was determined along a 120 m portion of the fault where the fresh surface rupture was confined to a single strand, based on our mapping (Fig. 2). In this area, the displaced features were mapped with an electronic theodolite and distance meter (total station), and a 1:1000-scale topographic map derived from more than 1000 data points was generated, using a 1 m contour interval.

ALLUVIAL CHRONOLOGY

The southwest margin of the Sierra Cucapa is marked by an abrupt, steep range front of Mesozoic igneous rocks produced by oblique slip along the Laguna Salada fault (Fig. 2). Coarse clastic debris shed off this range front and from the interior of the range has been deposited as alluvial fans along the margin of Laguna Salada (Fig. 2). Antecedent streams coalesce into broad bajadas or form solitary alluvial fan–fan deltas depending on spacing of channels draining the interior of the range. Coarse-grained alluvial deposits grade abruptly basinward into fine-grained mudstone and evaporite deposits. Several ages of alluvial deposits and their associated surfaces are represented by fans and terraces at different geomorphic levels (Fig. 3).

Determination of the relative age of displaced geomorphic surfaces was based on the degree of maturity of the soils developed in the deposits, and the extent of surface weathering. We described 26 soil profiles on surfaces of at least five distinct ages from exposures in hand-dug pits. Examples of typical soil profiles are listed in Table 1. A complete set of all 26 soil descriptions is also available[1]. Particle size distribution and secondary calcium carbonate percent were determined analytically for selected profiles (Mueller, 1984).

Absolute age was not determined for any of the Laguna Salada soils due to a lack of datable material in the alluvial deposits. Estimates of ages were made by comparing time dependent characteristics to dated soils

[1]GSA Data Repository item 9501 (complete set of soil descriptions) is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

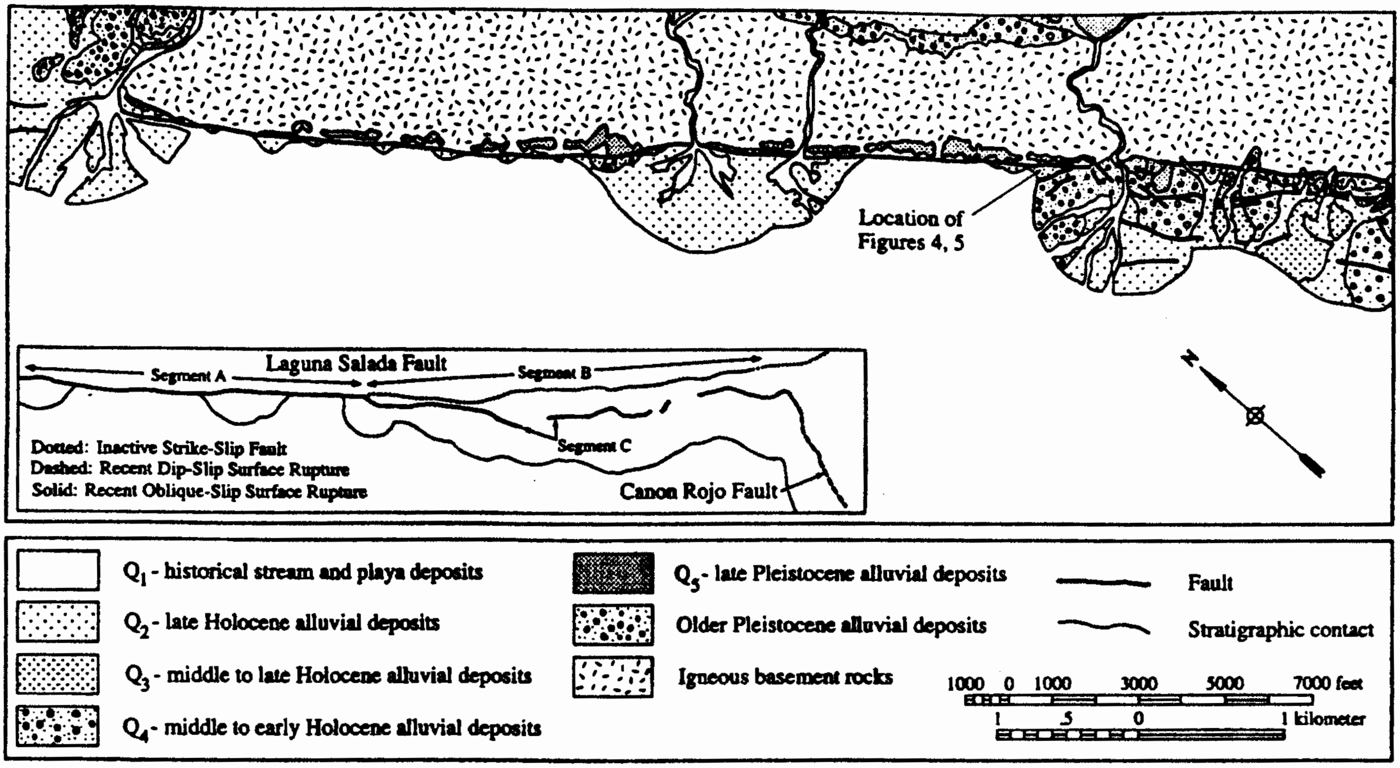


Figure 2. Geologic map of the southwestern margin of the Sierra Cucapa defining the active and inactive fault strands of the central portion of the Laguna Salada fault zone. Note the locations and recent activity of fault segments A, B, and C shown on the inset. Late Quaternary alluvial deposits include Q1 (youngest) through Q5 (oldest), which are progressively offset by increasingly higher fault scarps. The 1:1000 topographic map and illustration of the recent surface rupture (see Figs. 4 and 5 below) are located at the southeastern end of segment A. Detailed descriptions of scarp heights and displaced Quaternary deposits mapped at a scale of 1:10 000 are available in Mueller (1984) and Mueller and Rockwell (1991).

in the Imperial Valley (Goodmacher and Rockwell, 1990) and Mojave Desert (Reheis et al., 1989) which developed under a similar climate (hyperarid). The present climate in the Laguna Salada basin has a mean annual temperature (MAT) of 22–23 °C and a mean annual precipitation (MAP) of ~6 cm, similar to the Imperial Valley and Mojave Desert. This sequence of soils in Laguna Salada, or soil chronosequence, is used to place limits on the timing of late Quaternary faulting events, the average recurrence interval, and the slip rate on the Laguna Salada and Cañon Rojo faults.

The Laguna Salada soils develop in alluvial fans and terraces adjacent to and downwind from a playa, an abundant source of fine-grained dust and salts. The soils accumulated calcium carbonate, gypsum, and halite, with petrosalic horizons present in some profiles.

Members of the Laguna Salada soil chronosequence were differentiated by relative geomorphic position, the presence or absence of a cambic (Bw) or argillic (Bt) horizon, the extent of surface and subsurface weathering of clasts, the degree of accumulation of secondary calcium carbonate, and the development of rock varnish and desert pavement. The youngest member is represented by the Q1 deposits, which we presume are historic in age. These deposits are present in active stream channels (Fig. 2) and represent the initial conditions (parent material) for the other members of the chronosequence. Less than 1%–2.5% carbonate is present in these deposits in the three channels tested.

The youngest alluvial deposits that display some degree of visible soil horizonation (Q2) are exposed along incised stream channel bottoms, which do not appear to be active. Other Q2 deposits are present in areas of recent sediment accumulation. These include an isolated alluvial fan–fan delta adjacent to fault segment A (see inset, Fig. 2), alluvial fans at the northern end of the study area, and a region of coalesced fans deposited along the Cañon Rojo fault.

There is no visual evidence of weathering on alluvial surfaces that overlie Q2 deposits. Surficial clasts are unweathered and lack desert varnish. Soils developed in these deposits are Typic Torrifluvents consisting of a very thin (<2 cm), carbonate enriched A horizon of probable eolian origin (Table 1). Underlying C horizons contain less carbonate and consist of unconsolidated and unweathered sand and cobbles.

The most extensive alluvial deposits (Q3) present in the study area commonly underlie distal alluvial fan surfaces and terraces incised into the proximal and middle parts of fan segments. Soils on these deposits are classified as Camborthids or Calciorthids (Soil Survey Staff, 1975) and contain thin, 1–2 cm organic-poor ochric A horizons and poorly developed, 2- to 10-cm-thick cambic B horizons. Calcium carbonate has accumulated throughout the profile as disseminated, faint coatings on sand grains and clasts (weak stage I; Gile et al., 1966) (Table 1). Little or no varnish has developed on surficial clasts, and a desert pavement has not developed. Soils developed in Q3 deposits also have localized, sparse gypsum in some locations (e.g., LS-4).

Q4 alluvial deposits are sporadically ex-

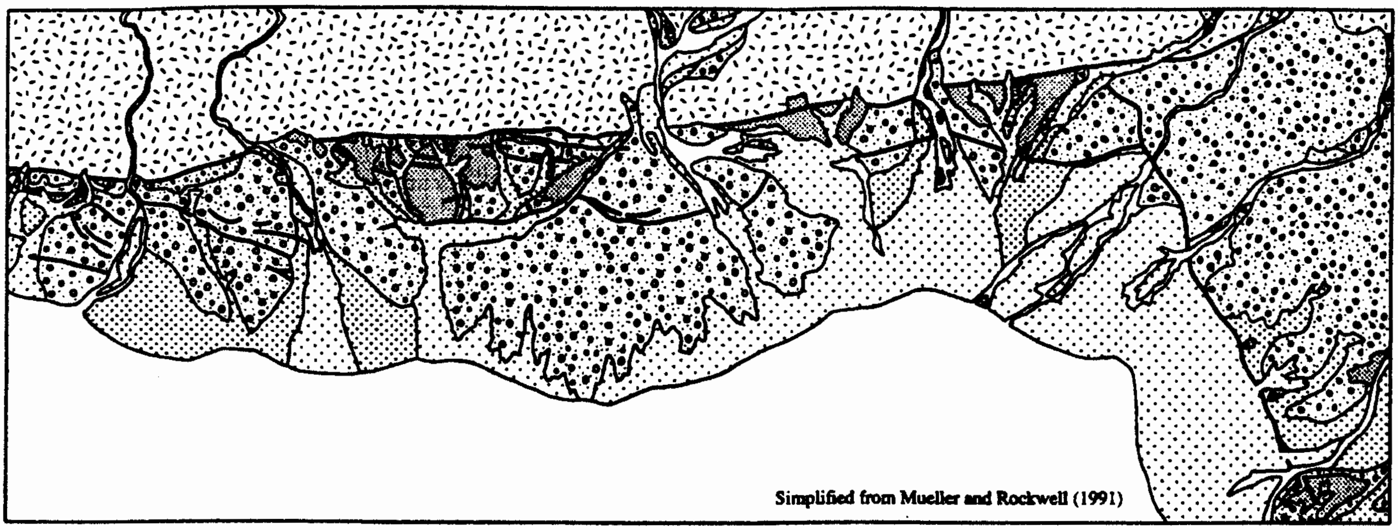


Figure 2. *(continued).*

posed along the length of the study area (Fig. 2) as isolated parts of alluvial fans uplifted on the footwall of the Laguna Salada fault. Soils developed in these deposits generally classify as Haplargids or Natrargids, contain thin (5–10 cm) argillic horizons, a gypsic horizon within and below the argillic horizon, and locally, a salic to petrosalic horizon at depths of <1 m (Table 1). Calcium carbonate is more concentrated in the upper part of the profile, but may be present throughout the exposure as very thin to moderately thick coatings on the undersides of clasts and weakly disseminated throughout the matrix on sand grains (stage I; Gile et al., 1966; Gile, 1975). Geomorphic surfaces developed above Q4 deposits generally do not have a well-developed desert pavement, although thin varnish is commonly present on surficial clasts. Most of the surface clasts on Q4 surfaces are strongly disaggregated due to salt weathering and display tafoni or cavernous weathering. Sand, generated from clast disintegration processes, blankets many of these surfaces.

The oldest alluvial deposits (Q5) in the study area lie on an erosional bench cut into the rangefront along fault segment A (see inset, Fig. 2). Other exposures are present on upraised lacustrine terraces cut across the footwall of the Cañon Rojo fault (Fig. 2). Soils developed in these alluvial deposits are Typic Haplargids and are characterized by 30- to 40-cm-thick argillic horizons and well-formed calcic horizons with stage II to II+ carbonate accumulation (Table 1; Gile et al., 1966; Mueller, 1984). These profiles also may contain gypsum and halite, but at much greater depths than in the younger Q4 soils. Q5 geomorphic surfaces are typified by well-formed desert pavements composed of surficial clasts covered by dark varnish.

Morphologic differences between soils developed in Q1 through Q5 alluvial deposits are largely due to an increase in age. The marked contrast in soil morphology between Q4 and Q5 alluvial deposits is also related to a change in climate at the end of the Pleistocene Epoch. Several studies have demonstrated that the decrease in MAP or increase

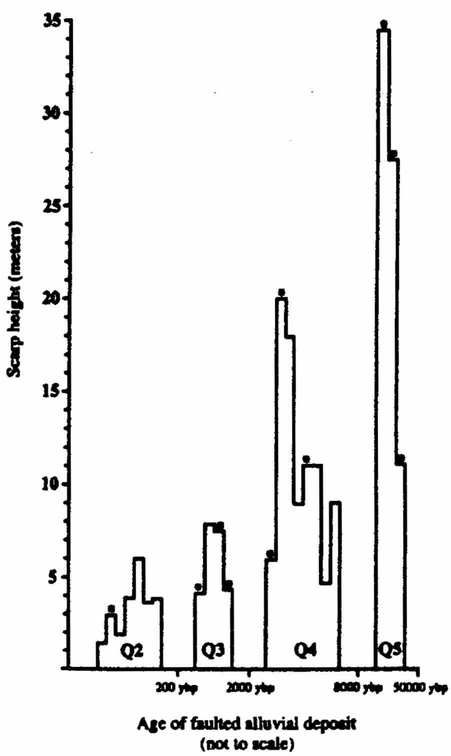


Figure 3. Graph of fault scarp height versus the age of the alluvial deposits they displace. Displacements record the vertical separation across fault scarps, and not the lateral component of displacement produced by oblique-slip events. Where accurate piercing points are preserved at the southeastern end of segment A (see Figs. 4 and 5), the vertical or normal component of slip produced by the most recent surface rupture is ~3.5 m; the lateral or dextral component of slip is ~4.0 m. Each bar corresponds to one topographic profile measured perpendicular to a scarp. Q2 deposits are offset by only the most recent surface rupture, with vertical separation ranging from ~2 to 6 m. Variation in vertical displacement may reflect the complex (i.e., noncontinuous) fault geometry and further segmentation of segments A and C. Offset of Q3 deposits reflects a larger variation in age than Q2 deposits, as indicated by soil profiles and weathering characteristics, indicating that some Q3 deposits are offset by more than the last surface rupture. Q4 deposits may be offset by as many as four to five events of a size similar to the most recent surface rupture. Starred bars on Q3, Q4, and Q5 profiles denote downthrown geomorphic surfaces buried by younger Q2 alluvium; these represent minimum vertical displacements of the older, uplifted deposits. Q2 columns marked by stars denote downthrown deposits covered by Q1 alluvium. Additional profiles are available in Mueller (1984).

TABLE 1. DESCRIPTIONS OF LAGUNA SALADA SOILS

Pedon horizon	Depth (cm)	Color	Texture	Structure	Consistency	Clay films	Carbonate (%)	Carbonate stage	Boundary	Sand (%)	Silt (%)	Clay (%)
					Q1 member, LS-32							
C	0 to 50+	10YR 6/2m; 7/2d	S	sg	lo	n.o.	1.30	n.o.	n.o.	97.30	1.60	1.10
					*Q2 member, LS-22**							
A	0 to 6	10YR 4/5/2m; 7/3d	LS-SL	M-1msbk-pl	so	n.o.	1.90	n.o.	a,w	75.60	19.40	5.00
C1	6 to 37	10YR 6.5/2m; 8/2d	S	M-sg	lo	n.o.	1–1.1	n.o.	c,w	90.60	7.30	2.10
C2	37 to 81	10YR 5/1.5m; 6.5/2d	S	M-sg	lo	n.o.	1.1–1.5	n.o.	c,w	90.50	7.60	1.80
2Bwkb	81 to 106	7.5YR 5.5/2m; 7/4d	S	M-1fsbk	so	1nbr, 2mkpo and cl (7.5YR 6/4m)	1.30	I	g,i	86.70	10.30	3.00
2BCk	106 to 150+	10YR 5.5/2m; 7.5/2d	S	M-1fsbk	so	n.o.	1.90	I	n.o.	88.50	8.90	2.50
					Q3 member, LS-28†							
A	0 to 2	10YR 5/3m; 6.5/3d	SL	M-1mpl	so	n.o.	2.90	I–	a,w	69.90	22.20	7.90
Bwk	2 to 12	10YR 4/2.5m; 7/4d	gS	M-1fsbk	so	vcobr (7.5YR 5/8m)	1.80	I	c,w	89.40	8.80	1.70
B1k	12 to 27	10YR 5/2.5m; 7/3d	gS	M-sg	lo	n.o.	1.90	I–	g,w	94.20	4.90	1.00
B2k	27 to 62+	10YR 4.5/2m; 7/3d	gS	M-sg	lo	n.o.	1.70	n.o.	n.o.	97.80	1.80	1.00
2Btb‡	-											
					Q4 member, LS-1#							
A	0 to 2	10YR 4/2m; 5.5/3.5d	LS	M-sg	so-lo	n.o.	1.50	I–	a,s	81.40	13.50	5.10
Btk	2 to 3	7.5YR 4/5m; 5/4d	SL	M-1fsbk	so-sh	1–2nbr and pf and po (5YR 5/6m)	2.70	I	a,w	79.30	11.70	9.00
Bky1	3 to 8	10YR 5/3m; 6/4d	gS	M-sg	lo	n.o.	1.60	I–	c,w	91.30	6.30	2.50
Bky2	8 to 27	10YR 4/2m; 5/3d	gS	M-sg	lo	n.o.	<1	I–	g,w	90.80	6.50	2.70
Bkyz	27 to 35	10YR 6/1.5m; 7/2d	S	M-sg	lo	n.o.	1.20	I–	g,w	94.60	4.20	1.20
Bkz	35 to 90	10YR 6/1.5m; 7/2d	S	M-msbk-sg	lo-vh	n.o.	3.20	I–	g,i	89.20	5.40	5.40
C	90 to 120+	10YR 6/1.5m; 6/2d	S	M-sg	lo	n.o.	1.00	n.o.	n.o.	97.40	1.70	<1
					*Q5, LS-7***							
A	0 to 1	10YR 4/4m; 6/4d	SL	M-1fcr	so-sh	n.o.	6.70	n.o.	a,w	62.90	25.60	11.50
Btk1	1 to 28	7.5–10YR 4/6m; 5/6d	LS-SL	M-1fsbk	so-sh	3ncl and br (7.5YR 4/6m)	20.80	II+	c,i	75.40	17.50	7.10
Btk2	28 to 60	10YR 4/3m; 5/4d	LS-S	M-1fsbk and sg	so	2ncl and br (7.5YR 4/6m)	3.60	I+	g,i	84.30	13.20	2.40
Bk1	60 to 143	10YR 5/3m; 6/3d	S-LS	M-sg	lo-so	vncl and br (7.5YR 4/6m)	5.00	II	d,w	87.70	12.00	<1
Bk2	143 to 185	10YR 4/2m; 5.5/3d	S-LS	M-sg and 1fsbk	lo-so	n.o.	2.90	I	c,w	84.70	10.00	5.30
2Bwkb	185 to 210+	10YR 4.5/3m; 5/4d	S	M-1fsbk and sg	so-lo	vcocl (7.5YR 4/6m)	4.40	I	n.o.	88.60	8.00	3.40

Note: Descriptions of soil development properties from selected pedons along the Laguna Salada fault. Descriptions, laboratory analyses, and nomenclature follow work by Soil Survey Staff (1975), Gile et al. (1966), and Dreimanis (1962). The complete set of 26 soil descriptions and related particle size and carbonate content analysis is available in GSA Data Repository item 9501. n.o. = not observed.

*Clasts appear unweathered in the upper 80 cm of profile. Surficial clasts are slightly pitted with no varnish development.

†No visible $CaSO_4$ or NaCl in profile. Surficial clasts are slightly pitted and exhibit no varnish. There is a sand apron from surface clast disintegration.

‡Not described at this pedon: Same as in LS-29.

#The Ckyz horizon has NaCl and $CaSO_4$ on undersides of clasts and dispersed throughout matrix. The Ckz horizon has a ruptic salic zone with between 5% and 30% NaCl, is petrosalic between 50 and 70 cm depth. Clasts appear highly weathered on the surface and in the upper 80 cm of profile. Granular disintegration of surface clasts has inhibited varnish.

**Clay in Btk is much higher in the upper several centimeters. The carbonate reported is the maximum measured for the Btk.

in MAT, or both, inferred for the climate at the end of late Pleistocene time resulted in a dramatic decrease in the depth interval at which carbonate accumulated (McFadden, 1982; 1988; Machette, 1985). The accumulation of gypsum and halite would also be shallower in Holocene deposits than that accumulated during the late Pleistocene climate.

Soils developed in Q2 through Q4 deposits are typified by thin profiles and very shallow, poorly developed cambic and argillic horizons. The presence of gypsum and halite at shallow depths is consistent with the present climate and implies that these are Holocene deposits. However, soils in Q5 deposits extend to considerably greater depth and exhibit clay and carbonate accumulation at depths consistent with substantially higher rainfall than represented by the Q4 deposits (Gile et al., 1981; Machette, 1985). The salic horizons in the Q4 deposits are present at depths similar to the lower parts of the Q5 argillic horizons, suggesting the Q5 deposits record soils developed under two climatic regimes.

Studies of *Neotoma* (packrat) midden sites in the southwestern United States indicate that the climate change, from wetter to drier, occurred between 8000 and 12 000 yr B.P., at the end of the Pleistocene Epoch (Wells, 1976; Van Devender, 1977), or ~10 ± 2 ka. We use this age as the maximum likely age of the older Q4 deposits. Q5 soils must be older by some degree to allow for their development under wetter conditions prior to the climate change.

More direct information on the ages of the Laguna Salada chronosequence may be derived by comparison of the Q2 through Q5 soils with dated soils in the Mojave Desert at Silver Lake (MAT = 21 °C, MAP = 8.3 cm; Reheis et al., 1989) and at the Coyote Mountains in the western Imperial Valley along the Elsinore fault (MAT = 22 °C, MAP = 7.5 cm; Goodmacher and Rockwell; 1990) (Table 2). The Silver Lake study may be the strongest analog because it has well-defined age control for soils in the time frame of interest and a climate and parent material similar to Laguna Salada. The Coyote Mountain study is also useful for the late Holocene soils based on its proximity to Laguna Salada, similar-aged deposits, climate, and age control.

The Laguna Salada (LS) Q2 soils are very poorly developed and are probably <200 yr old, based on comparison of soil development index, soil color, and carbonate stage to both the Silver Lake (SL) Qf6 and Coyote Mountain (CM) Q2 soils. Similarly, LS Q3 soils are weakly developed compared to these other soil sequences. Soil development index (Table 2) of the LS Q3 soils is similar to the SL Qf5 soil and lies between the CM Q2 and Q3 soils. Based on these comparisons, we assign an age of 0.2–2 ka to the LS Q3 soils. This age range in Laguna Salada soils is reasonable, based on the considerable variation evident in profiles described from Q3 deposits from separate alluvial fans (Table 1).

TABLE 2. SOIL SUMMARY FOR LAGUNA SALADA AND SIMILAR SOILS

Soil Member	Classification	SDI[*]	Secondary clay % max.	Max. carb. (%)	Carbonate stage max.	Max. dry color	Thickness Bw/Bt (cm) mean (range)	Age (ka)
				Laguna Salada chronosequence[†]				
Q1	Raw alluvium	0	0	1–2.5	0	10YR 7/2	0	<0.05
Q2	Torrifluvent	0.5–0.8	0	1–6.6	0	10YR 7/3.5	0	<0.2
Q3	Camborthid	0.3–2.3	0–1	1.6–2.9	I–	7.5–10YR 6/4	5.2 (2–10)	0.2–1
Q4	Haplargid	2.9–8.1	5.2–14.5	2.2–4.7	I	7.5YR 5/5	6.5 (1–9)	4–8
Q4+	Haplargid	9.6–18.2	5.6–8.5	2.2–3.4	I+	7.5YR 5/5	20 (19.5–20)	6–11
Q5	Haplargid	21.2–32.3	5.8–12.7	3.9–20.8	II to II+	7.5YR 5/6	29 (21–38)	15–50
				Silver Lake chronosequence[§]				
Qf6	Raw alluvium	0	n.d.	n.d.	0	10YR 7/3	0	<0.05
Qf5	Torrifluvent	1–3	n.d.	n.d.	0	10YR 7/4	0	0.2
Qf4	Torrifluvent	4–14	n.d.	n.d.	II–	10YR 7/4	7	2
Qf3	Torrifluvent	5–15	n.d.	n.d.	II	7.5YR 5/6	7	6
Qf2	Haplargid	7–33	n.d.	n.d.	II	7.5YR 5/6	29	11
Qf1	Haplargid	20–58	n.d.	n.d.	II	7.5YR 5/6	22	35
				Coyote Mountains chronosequence[#]				
Q2	Torrifluvent	1.1	0	6.5–9	I–	10YR 6/3	0	0.3–0.5
Q3	Torrifluvent	3.1	0	7.9–8.1	I–	10YR 6/3	0	1–2
Q4	Torrifluvent	5.8	0	7.8–8.4	I	10YR 7/3	0	2–3
Q5	Calciorthid	10.7		4.1–7	I+	10YR 6/4	19	9–20
Q6	Calciorthid	14.1		9.4–14	II+	10YR 7/4	6	20–75
				New Mexico chronosequence[**]				
Organ II	Camborthid	n.d.	12		I	5YR 4.5/4	10	2.2
Organ I	Haplargid	n.d.	15		I	5YR 5/4	46	4.7
Isaacks Ranch	Haplargid	n.d.	18		II	5YR 5/5	46	8–15

Note: Summary for the comparison of the Laguna Salada soil chronosequence with other well-dated sequences in the Mojave Desert (Silver Lake) and the Imperial Valley (Coyote Mountains). n.d. = not determined.

*Soil development index.

†Mean annual temperature (MAT) = 23 °C, Mean annual precipitation (MAP) = 6 cm, Elevation = 0–50 m.

§MAT = 21 °C, MAP = 8.3 cm, Elevation = 300 m.

#MAT = 22 °C, MAP = 7.5 cm, Elevation = 200–230 m.

**MAT = 15.6 °C, MAP = 16–21 cm, Elevation = 1300 m.

The Laguna Salada Q4 soils differ substantially in morphology from Q1 through Q3 soils, due in part to their greater variation in age. Q4 soils with markedly different physical characteristics are apparent along short segments of the same fault strand where they are displaced different amounts (see Mueller and Rockwell, 1991; their Fig. 4). The youngest (most weakly developed) Laguna Salada Q4 soils may correlate with the SL Qf4 and CM Q4 soils based on soil development index, color, and carbonate morphology. Older LS Q4 profiles readily correlate to the SL Qf3 soils based on these same criteria. Laguna Salada Q4+ soils (profiles LS-24 and LS-25) are similar to the SL Qf2 profiles. Based on these comparisons, we assign an age range of 2–8 ka for the LS Q4 soils, with the Q4+ profiles being older and probably in the range of 8–12 ka. These age assignments agree with differences in thickness of Bt horizons, which average 6–7 cm for the LS Q4 but ~20 cm for the Q4+ soils, suggesting that the Q4+ soils may have begun to develop before the end of the Pleistocene Epoch.

Laguna Salada Q5 soils are clearly Pleistocene in age based on their depth of development and carbonate morphology. Comparison to Silver Lake suggests that they correlate with the SL Qf1 deposits, although the Qf2 soils are also a candidate. The best correlation to the Coyote Mountains soils is Q6, based primarily on carbonate morphology; therefore we tentatively assign an age range of 15–50 ka for the LS Q5 soils.

SLIP MAGNITUDE OF THE MOST RECENT EVENT

The Laguna Salada fault zone (Fig. 2) is expressed as several oblique-dextral and dextral fault strands whose recency and sense of slip has varied during late Quaternary time (Mueller and Rockwell, 1991). The northwest part of the study area is marked by a single range-bounding fault strand (see segment A on inset, Fig. 2) that dips 55°–70° southwest. At the south end of segment A (Fig. 2), the fault splits into three strands across a small releasing bend. The predominance of active slip is transferred to the southwest onto faults (Fig. 2) that displace Q2 through Q5 alluvial surfaces. The range-bounding strand continues to the southeast (segment B, Fig. 2) and has had only minor (i.e., <1 m) vertical Holocene displacement associated with it. Additionally, the surface of fault segment B changes dip direction repeatedly from the northwest to the southeast, defining a helical fault surface (see Mueller and Rockwell, 1991, for more detailed fault maps). It is likely that this fault strand (segment B, Fig. 2) abruptly steepens with depth, forming a characteristic convex-up shape in cross section (Sylvester, 1988). We regard this fault strand as a dominantly strike-slip fault that is mostly inactive at the present.

Segment C is marked by abrupt fault scarps in Q2 through Q4 deposits (Fig. 2). It and other smaller faults collectively exhibit scarps up to 18 m in height. The surface activity of smaller fault strands die out ~2 km southeast of the releasing bend; segment C is the active strand from there southeast to the Cañon Rojo fault. At Cañon Rojo, rupture during the past several earthquakes has continued to the southwest along the Cañon Rojo fault for ~2.5 km (Mueller and Rockwell, 1991).

The most recent large earthquake along the fault produced free faces in alluvium and freshly exposed fault surfaces up to 5 m high that extend for at least 22 km from the northwestern extent of our study area (see inset, Fig. 2) southeast to, and along, the Cañon Rojo fault. Recent ground rupture is not evident in a field of sand dunes several kilometers northwest of the study area; however, scarps at the southern margin of the dune field express up to 2 m of vertical displacement. Thus it is likely that the rupture continued for some distance to the northwest. Isaacs (1987) mapped the Laguna Salada fault in the Yuha Buttes area north of the international border and found no well-preserved evidence of a very recent earthquake, although minor vertical separation may not have been preserved here for more than a few decades.

Surface rupture from the most recent earthquake displaces deposits as young as Q2, which appear to have been broken by only that event, based on scarp morphology (in particular, the height of free faces). Many of the Q3 deposits were also broken by only this event, although Q3 deposits 1 km north of the Cañon Rojo fault (Fig. 2) express roughly twice the vertical separation produced by that earthquake. Q3 deposits at this location may be offset by a composite scarp produced by two events, based also on scarp morphology. The vertical separation produced by the most recent surface rupture (Fig. 3) represents the scarp heights measured primarily from exposed bedrock surfaces and displaced Q2 deposits.

The southernmost part of segment A (Fig. 2) preserves several displaced alluvial cones and channels that provide unambiguous correlation and slip across the fault for

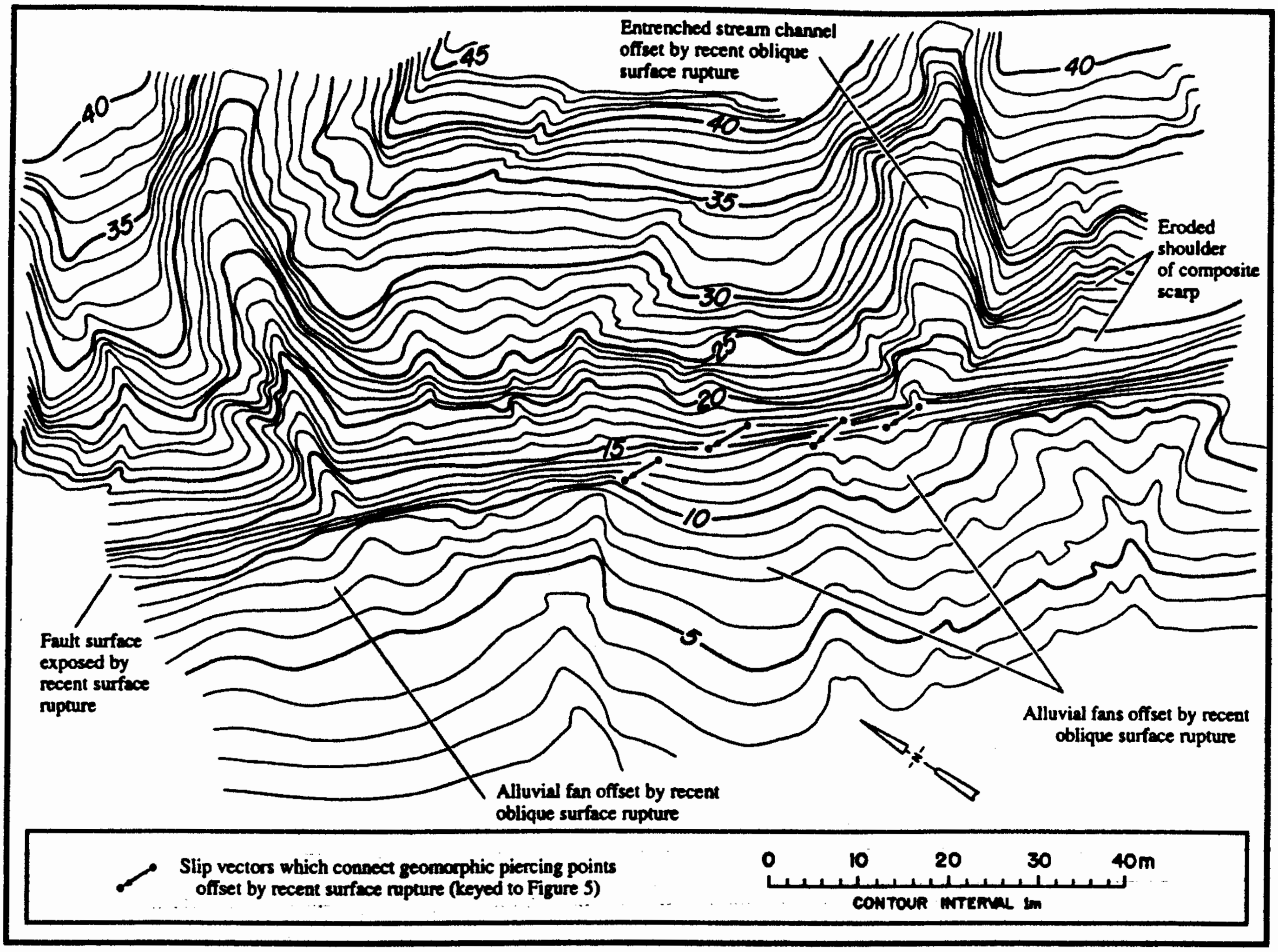


Figure 4. Topographic map compiled from elevation points determined with a total station distance meter. Two entrenched stream channels are evident in the upper half of the figure on the uplifted side of the fault scarp. The southwest-facing scarp is recorded by the linear contours in the center of the figure. The recent surface rupture along the fault is defined by the closely spaced contours at the base of the scarp. At least one other faulting event is expressed as a more weathered band above the recent surface rupture. Small alluvial fans are present to the southwest on the downthrown side of the fault. The heads of the alluvial fans once located at the end of the entrenched stream channels are now obliquely offset (3.5 m of normal, 4.0 m of dextral) by the recent surface rupture. Arrows connecting dots along the fault scarp are vertical projections of slip vectors that connect microtopography offset across the recent surface rupture. These include the heads of alluvial fans and points where fans merge at the base of the scarp. Corresponding points at the top of the scarp include the ends of entrenched stream channels, which debouch at the edge of the rangefront, and features along the top of the fresh fault surface. Many of these features, in particular the top of the most recent surface rupture, are more readily apparent on Figure 5, a side view of the fault scarp.

the most recent event. Several specific piercing points, including offset alluvial fan heads and topographic lows where fans merge, yield 4 m of strike-slip and 3.5 m of dip-slip at this location (Fig. 5). The vertical separation across the fault for this event in this area varies from ~2.5 m to nearly 5 m due to the lateral juxtaposition of topographic highs and lows (Fig. 5). Based on the slip determined from the piercing points, ~5.3 m of oblique slip was produced in this earthquake along the central part of the rupture. The vertical separation for this event averages between 2 and 4 m, when summed across the different fault strands, between the Cañon Rojo fault and the north end of the study area (Fig. 3). Based on empirical data that relate earthquake magnitude, surface rupture length, and displacement (e.g., Wells and Coppersmith, 1994), the recent ground rupture on the length of the Laguna Salada fault that we studied continues to the northwest for an unknown distance across the dune field.

To calculate the minimum moment and magnitude of this event, we use 5 m as the average slip over the distance where we can demonstrate scarps with 3–4 m of vertical separation (~20 km). A value of 14 km for fault width was also used, which assumes ~12 km of brittle crust and an inclined fault of 60°. These values are based on the depth of seismicity in Laguna Salada and the average dip of the active fault at the surface. This yields a moment of 4.2×10^{26} dyne-cm, or an earthquake with a moment magnitude

Figure 5. Line drawing of a photograph taken of the recent surface rupture at the same location as the detailed topographic map shown in Figure 4. View is toward the northeast, perpendicular to the fault scarp. Note the fault surface (the band of freshly exposed bedrock) at the base of the scarp. The upper boundaries of recent surface rupture correspond to displaced features at the base of the scarp and are denoted by the slip vectors also marked on Figure 4. The vectors are similar in magnitude and orientation to, and record the dextral component of, slip produced by the recent surface rupture, which is rarely preserved along the fault zone. Note also the highly weathered band of pitted rock above the planar fault surface exposed by the recent surface rupture. This older fault exposure appears to have been produced by an earthquake of magnitude similar to the recent Mw 7.1 surface rupture.

(Mw) of ~7.1. The actual slip at depth may have been equal to or greater than the surface displacement, so this moment estimate is considered a minimum. Furthermore, slip could have extended farther north for an additional 10+ km, resulting in a larger moment and earthquake.

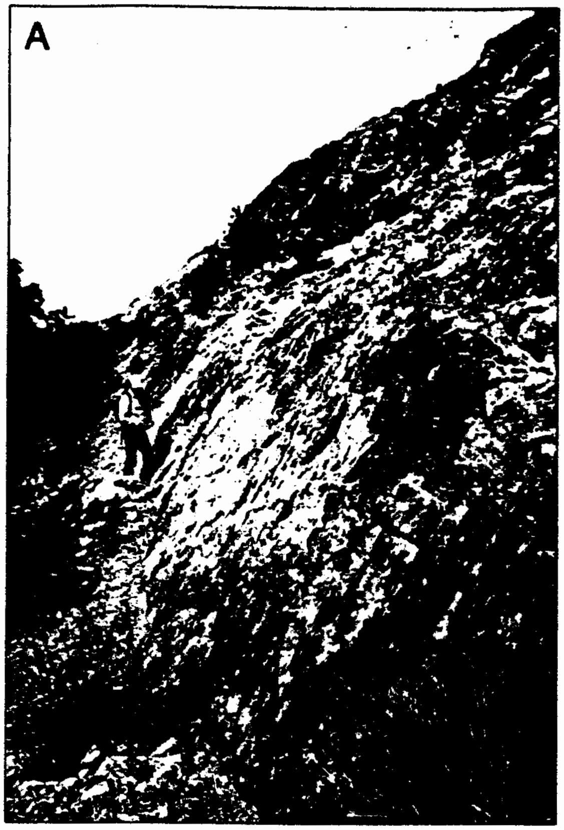
TIMING OF THE MOST RECENT EVENT

The timing of the most recent event is addressed from three perspectives: the age of the most recently displaced alluvium, the preservation of the scarps produced in this event, and the historic record. The youngest deposit displaced in this earthquake is the Q2 alluvium, which is estimated at <200 yr old. The soils are so weakly developed that the event could well lie within the historic period for this area, about the past 150 yr. An earthquake of this magnitude should have been reported if it did occur during the historic period.

The extent of preservation of free faces along most of the length of the rupture also indicates an historic or near historic event. Using scarps in only the Q2 deposits, which did not result from recurrent slip, between 20% and 80% of the scarp height remains as a free face in unconsolidated gravelly alluvium (Figs. 6A and 6B). Using scarp degradation relationships developed for normal faults in the Great Basin, this indicates displacement within the past 1–2 centuries (Wallace, 1977; Bucknam and Anderson, 1979). Laguna Salada scarps are at least as well preserved as scarps from the 1915 Pleasant Valley and the 1954 Dixie Valley–Fairview Peak earthquakes in Nevada. This also indicates that the Laguna Salada rupture may be historic in age.

The large February 23, 1892, earthquake may have occurred on the Laguna Salada fault zone based on Rossi-Forrell isoseismals for that event (Strand, 1980). He estimated a magnitude of 7–7.5 for that event, consistent with the rupture required to produce the size of the scarps that we describe here. Other interpretations of the historic record of shaking for this event place it farther west, because the aftershocks were more strongly felt in San Diego, California, than at Yuma, Arizona (Toppozada et al., 1981). We concur with Strand's (1980) placement in the Salton Trough based on the lack of known late Quaternary faults in the region where Toppozada et al. (1981) placed the event and explain the felt effects by attenuation in the Imperial Valley sedimentary fill (e.g., Anderson et al., 1989).

The youthfulness of the alluvium displaced by the most recent event is consistent with an historic or near historic event. The February 1892 earthquake has been located in the region of the Laguna Salada fault based on felt reports (e.g., Strand, 1980); thus it is the likely candidate earthquake to have produced these scarps. There is no other earthquake recorded in historic time in the Imperial Valley region for which a ground rupture is known that is large



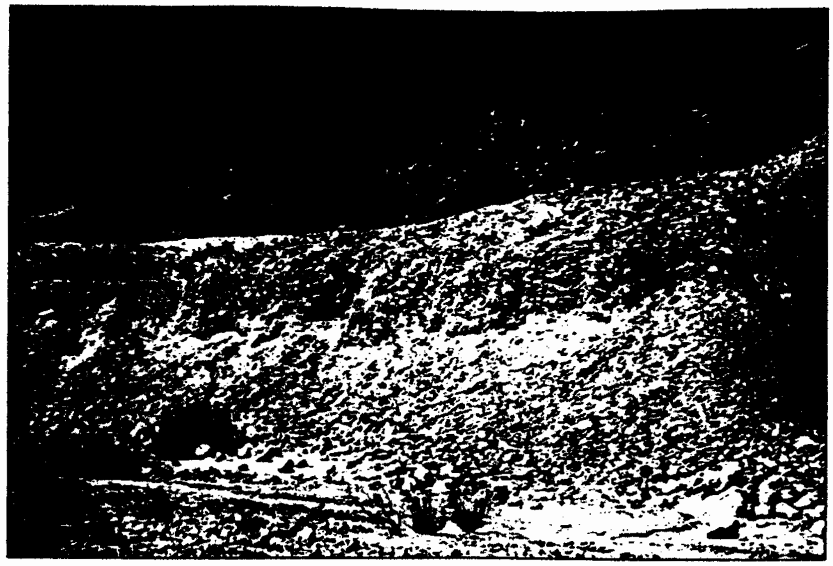


Figure 6. (A) Photograph of fault surface produced at the edge of the crystalline rangefront by the most recent surface rupture. This fault scarp, which displaces Q2 deposits, is marked by a smooth surface composed of fault breccia. The upper edge of the smooth fault surface is marked by an abrupt transition to a more shallowly inclined and intensely pitted surface. The marked increase in weathering on the two fault surfaces indicates the significantly longer time period between the last recurrence interval (0.5–2.0 k.y.) and the period of time since the most recent surface rupture (0.1 k.y.).

(B) Photograph of the scarp produced by the recent surface rupture where it displaces Q4 deposits in the central portion of segment C (see inset, Fig. 2). The well-preserved, vertical free face in unconsolidated alluvium indicates the recency and probable historic nature of the fault scarp.

enough to have produced the Laguna Salada scarps. Furthermore, scarps on nearby faults lack evidence of recent activity. Therefore, we attribute the more recent scarps in our study area to this historic earthquake.

ESTIMATION OF THE RECURRENCE INTERVAL AND SLIP RATE

Recurrent Holocene slip is evident by the greater scarp heights in progressively older Holocene deposits (Fig. 3). The Q2 deposits appear to be displaced only by the most recent event. Most Q3 deposits are also displaced only by the most recent ground rupture, based on scarp morphology. Other scarps which offset Q3 deposits display more vertical separation, although with similar free face heights. These may, therefore, be a product of more than the most recent ground rupture.

Recurrence Interval

The interval between the two most recent ground ruptures is approximated by the range in age between the Q2 and Q3 deposits, or ca. 0.2–2.0 ka. The substantial difference in age between the Q2 and Q3 deposits therefore places the penultimate surface rupture as occurring between 0.2 and 2.0 ka.

Another indication of the time between events is represented by the degree of weathering on fault surfaces exposed during earlier earthquakes at any given location. The fault surfaces exposed during the past several events are evident as distinct bands that display substantial differences in their inclination, amount of weathering and surface pitting on the bedrock. Surfaces exposed during the most recent ground rupture are relatively fresh, with minor salt weathering and crystal pitting (Figs. 5 and 6A). There has not been sufficient time to produce cavernous weathering of the exposed rock. The fault surface exposed from the penultimate event, however, is strongly pitted and weathered, with cavernous weathering exhibited locally (Fig. 6A). It is about the same height as the most recent surface rupture. The third fault surface back in time (i.e., the most elevated one) on the composite range-front scarp displays substantial weathering and erosion of the rock to the point that the slope is recognizably less than the band produced from the most recent rupture (Fig. 5). These observations indicate that enough time must have occurred between seismic events to allow for substantial weathering of the exposed bedrock fault surface. Based on the relatively small amount of weathering of the most recently exposed scarps, which represent <200 yr of degradation, it is clear that the return time is considerably longer than the time since the last movement. Based on these observations and the probable age range of the Q3 deposits, we suggest that the penultimate event occurred ca. 1–2 ka.

The youngest Q4 deposits are vertically separated by at least three times the displacement expressed from the most recent ground rupture, and most Q4 scarps apparently represent about three similarly sized events. The minimum age for Q4 deposits as 2 ka (Table 2) suggests a recurrence interval of at least 0.7 k.y. The most abundant soil data on the Q4 soils are in the area where segments A, B, and C join (Fig. 2); these soils provided many of the descriptions on which their age of 5 ± 3 ka is based. Scarps across these Q4 deposits are 18 m high, or about four times the most recent surface rupture; these yield an average recurrence interval of ~0.5–2 k.y.

The oldest Q4 member, designated Q4+ in Table 2, exhibits scarps at least 20 m high (these are a minimum, because the corresponding downthrown surface is buried by Q2 alluvium), or at least five events similar to the most recent surface rupture. With the inferred age of 10 ± 2 ka for this unit, a recurrence interval of ~1.6–2.4 k.y. is suggested.

All these data generally agree and suggest an average recurrence for large displacement events of ~1–2 k.y. Further resolution would require more precise dating of the scarps and deposits displaced by this fault. This may prove difficult with conventional techniques; we found no charcoal, wood, or other datable organic matter in any of the dozens of soil pits or hundreds of meters of exposed arroyo walls that we examined.

Our estimates of recurrence interval are supported within a factor of two by geodetic studies and dislocation modeling by Savage et al. (1994), which indicate rates of ~4 mm/yr of dextral slip and 7 mm/yr of normal slip across several active faults parallel to the northwest-southeast axis of the Sierra Cucapa. Further refinement of these data awaits detailed paleoseismic studies of other active faults in the Sierra Cucapa and Mexicali Valley.

Slip Rate

The evidence for horizontal displacement for the most recent event is clear along only the central part of the fault zone, at the southeast end of segment A (Fig. 2), where slip is concentrated within a narrow zone. Even in this area, however, Q3 and older alluvial deposits are rarely preserved at the surface on the downthrown hanging wall block because of burial by younger alluvium (Figs. 2 and 3). Direct evidence for the slip vector for previous events is therefore lacking in most cases, and we infer that it is similar to that which occurred during the most recent event. This inference is reasonable, because the dip-slip component in at least the two or three previous earthquakes is similar to that experienced in the most recent event, and because the geometry of the fault at its intersection with the normal-slip Cañon Rojo fault requires a component of strike-slip on the Laguna Salada fault (Mueller and Rockwell, 1991).

The estimated age of the Q4 deposits of 5 ± 3 ka and their vertical separation of 11–20 m yields an average vertical displacement rate of ~3 mm/yr, with a potential range of 1.4–10 mm/yr. We believe that a rate in the upper part of this range is probably not reasonable based on the rate for the Q4+ deposits, ~1.7–2.5 mm/yr, and the Q5 deposits, ~0.7–2.3 mm/yr. If the average vertical displacement rate is 2–3 mm/yr, and all of the Holocene surface ruptures produced similar ratios of vertical to horizontal slip (~1:1), then a strike-slip rate of ~2–3 mm/yr is suggested. This value is also very close to that determined for the Elsinore fault in the Coyote Mountains (Pinault and Rockwell, 1984; Rockwell, 1990) and suggests that much of the Elsinore slip is transferred to the Laguna Salada fault.

SUMMARY

We draw several conclusions regarding the late Quaternary behavior of the Laguna Salada fault. Our studies suggest that the sense of slip along the Laguna Salada fault is oblique and that the most recent event produced about an average of 4 m of dextral slip and 3.5 m of normal slip along the central part of the range front. The most recent earthquake displaced very young alluvial deposits and is probably the widely felt 1892 northern Baja California event based on historic accounts and the freshness of the free faces on the fault scarps. Older alluvial deposits displaced progressively greater amounts and indicate recurrent Holocene activity. The recurrence interval suggested by the displacements and soil-age relationships is on the order of 1–2 k.y. The lateral slip rate is ~2–3 mm/yr, similar to that of the southern Elsinore fault north of the international border.

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